CALIFORNIA ENVIRONMENTAL PROTECTION AGENCY
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STAFF PROPOSAL REGARDING REDUCTION OF GREENHOUSE GAS EMISSIONS FROM MOTOR VEHICLES

MOBILE AIR CONDITIONING SYSTEMS— INDIRECT EMISSIONS

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Mobile Air Conditioning Systems - Indirect Emissions

Background

The contribution of mobile air conditioning systems (MACs) to exhaust CO_2 emissions can be attributed to transportation of the unit's mass and operation of the system during driving. These emissions are commonly called the "indirect" emissions. It is estimated that indirect emissions can be reduced up to 30 to 50 percent by reducing the engine load requirements from MACs. This can be accomplished by utilizing more efficient variable displacement compressors (VDC), condensers and evaporators with improved heat transfer, and better control systems.

The engine load requirements for VDCs are lower than that of fixed displacement compressors (FDCs) because, rather than providing a constant flow of refrigerant with on/off cycling, VDCs modulate compressor displacement, allowing refrigerant flow to vary to meet cooling demands. As cooling demands increase, the benefits of VDCs decrease relative to that of FDCs. For the limited conditions that require maximum compressor displacement, the benefit of VDCs over FDCs approaches zero.

The use of VDCs is a currently available technology. Though not yet commonly employed in the United States, VDCs are more prevalent in the European Union. The on/off cycling associated with FDCs noticeably impacts the performance of smaller engines. Consequently, in the European Union, where the average engine displacement is less than two liters, VDCs provide significant improvement to engine performance.

Another means to enhance MAC operation is to control the amount of outside air admitted to the passenger compartment relative to recirculated air. This reduces the amount of hot air from outside that needs to be cooled by the system. This strategy can be applied to either manually or automatically controlled MACs and is also currently feasible.

Additionally, MAC performance can be improved by the elimination of "air reheat". A characteristic of MACs equipped with FDCs is the tendency in mild conditions to overcool and then reheat the air to provide a moderate level of cooled air. Because VDCs modulate refrigerant flow, they can be adapted to eliminate air reheat. However, because elimination of air reheat requires automatic climate controls, and manual controls are most prevalent in the United States, this feature was not assumed for modeling the benefits of improved MACs.

In addition to indirect emissions, MACs also release refrigerant emissions, which are commonly referred to as "direct" emissions. The current refrigerant in new MACs, HFC-134a, has approximately 1300 times the global warming potential (GWP) of CO_2. Consequently, even low level refrigerant emissions can be problematic. Besides developing more "leak-tight" MAC components and reducing other opportunities for refrigerant release, another possible strategy is to substitute the existing refrigerant with one that has a lower GWP. Substitution with the refrigerant HFC-152a appears to have significant near-term potential. The merits of refrigerant substitution with HFC-152a and other aspects of direct emissions are discussed in more detail in Section II.C of the report. However, because HFC-152a transfers heat more efficiently than HFC-134a, there are also gains to be made with HFC-152a substitution from a CO_2 emission reduction standpoint. While the driving force behind substitution with HFC-152a may be the reduction in direct emissions, the likelihood of near-term implementation is favorable and therefore the indirect benefits were included in the vehicle simulation modeling.

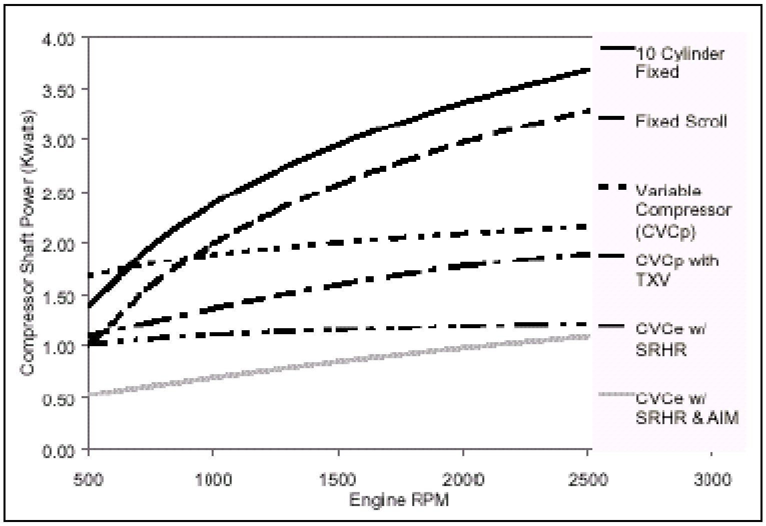
Other MAC CO_2 reduction strategies aim to reduce the vehicle solar load. Use of solar reflective glass, modified glass angles, improved cabin insulation, altering interior and exterior colors, and other measures can significantly reduce the solar load and consequently ease the engine load from MACs. However, these strategies are independent of MAC design and were not incorporated into the simulation modeling. In the future, benefits from these types of measures may be credited through the incorporation of whole vehicle testing that simulates solar load. However, presently such testing is neither reliable nor accurate, and needs further development.

Vehicle Modeling

Vehicle simulation modeling was performed to estimate the CO_2 benefits from use of an improved MAC for each of the five vehicle classes. Given the considerations discussed in this section, operation with a conventional fixed displacement compressor was compared to that of a system comprised of a variable displacement compressor with external controls, air reuse strategy, and substitution with HFC-152a refrigerant.

To perform the CRUISE simulation modeling, mobile air conditioning (MAC) power loads were characterized for fixed displacement compressors (FDCs), and for the system combination of variable displacement compressors (VDCs) with external controls, air reuse strategy, and HFC-152a as the refrigerant. The MAC power loads were derived by first examining curves from Forrest and Bhatti (2002). These curves establish MAC compressor shaft power demand versus engine rpms for several types of air conditioning systems, as shown in Figure 1. All systems shown in the figure use HFC-134a as the refrigerant. Testing was performed with a system test stand that incorporated the entire heating, ventilation, and air conditioning system, and used a torque transducer for measuring the torque required for compressor shaft rotation. Ambient conditions during testing were 80.1 °F and 60% relative humidity.

Figure 1. Variation in Power Demand Relative to a 215 cc FDC Base System (Forrest & Bhatti, 2002)



Note: The power demand figures include the effect of compressor "on/off" cycling as required to maintain efficient evaporator function at 80.1 °F and 60% relative humidity ambient conditions. SHSR stands for Series Reheat Reduction Strategy, AIM stands for Air Inlet Mixture (forced recirculation), and TXV stands for Thermal Expansion Valve.

In Figure 1, displacement for the FDC is 215 cc. Because average FDCs are assumed to be around 180 cc, all data in the curves were scaled down to a base FDC displacement of 180 cc. Next, the compressor shaft power demands were converted to crankshaft power demands by assuming a belt transmission efficiency of 97 percent (typical belt losses are 2 to 4 percent).

However, none of the curves in Figure 1 specifically characterizes a system comprised of a VDC with external control, air reuse, and HFC-152a as the refrigerant, the system selected for modeling. Instead, other combinations are shown in the figure. As a result, the desired combination of features, VDC with external control and air reuse, had to be isolated from the curves. Corrections for HFC-152a will be made later from another source of data.

To isolate the desired system combination, the benefit of reheat reduction had to be removed. This was accomplished by normalizing the VDC with reheat reduction plus air recirculation loads (SRHR & AIM in the figure) to VDC with reheat reduction alone (SRHR in the figure). The resulting ratio was then applied directly to the base electronic control unit without reheat reduction or air recirculation (CVCp with TXV in the figure). Next, it was assumed that the blower motor demands an additional 0.25 kW, which was added to the revised

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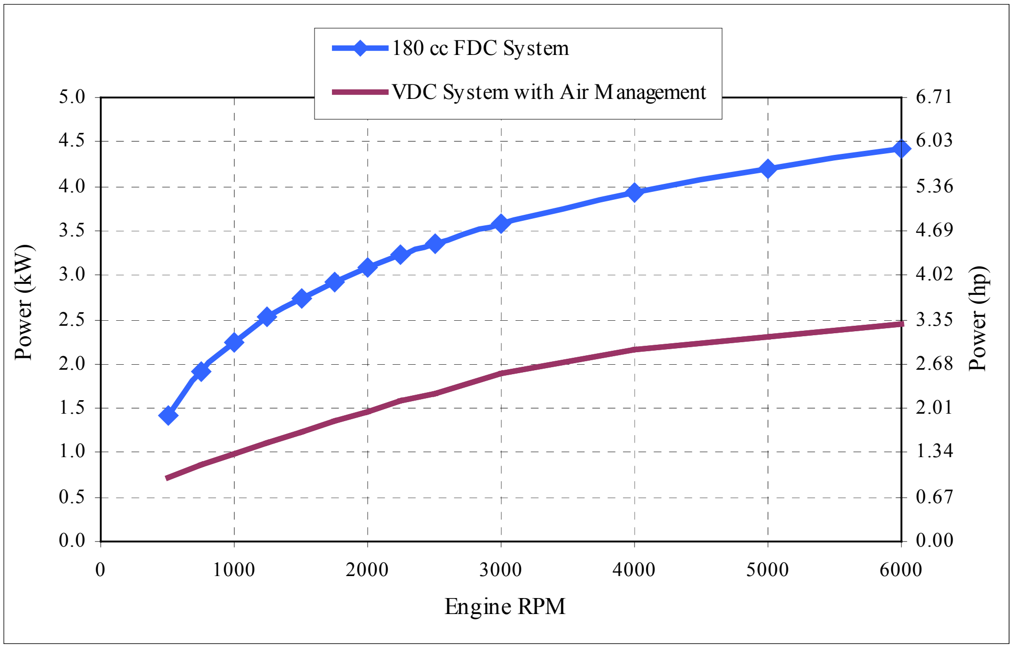
curves for both the FDC and VDC systems. MAC power demands were now characterized for varying engine rpms, as shown in Figure 2.

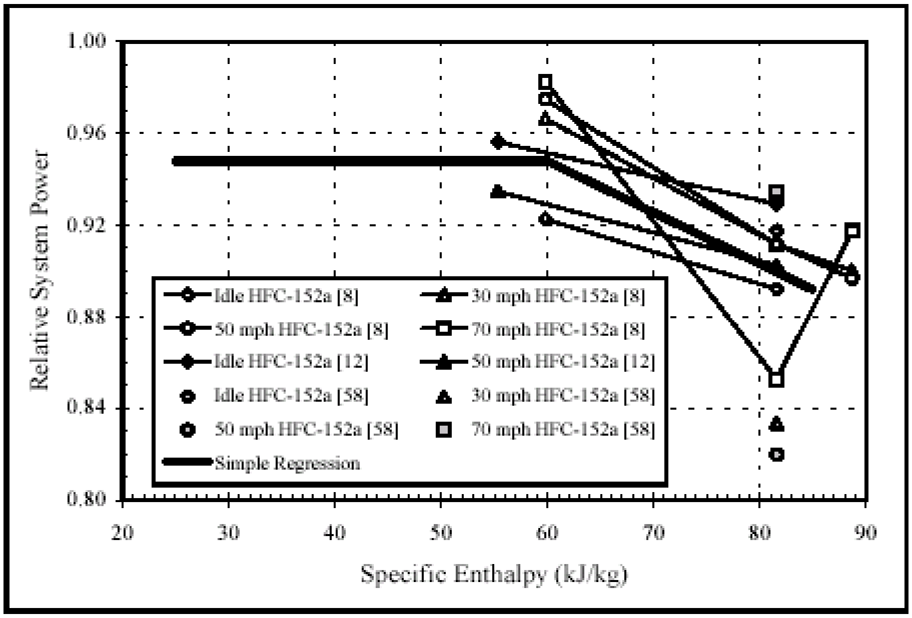
Figure 2. MAC System Power Demand at the Crankshaft



As an aside, it is important to note that the ambient conditions used for testing by Forrest and Bhatti (2002) are also applicable to the CRUISE simulation modeling. Consider that, based on an extensive state-by-state thermal comfort analysis conducted by the National Renewable Energy Laboratory (NREL), average ambient conditions during MAC operation in the United States are 77° F and 69 percent relative humidity (Johnson, 2002). Factoring in altitude, the resulting specific enthalpy is 60.9 kilojoules per kilogram. Specific enthalpy for the Forrest and Bhatti test is approximately 61 kilojoules per kilogram, which is virtually identical, demonstrating that no adjustments to ambient conditions were needed to relate the Forrest and Bhatti data to our modeling inputs.

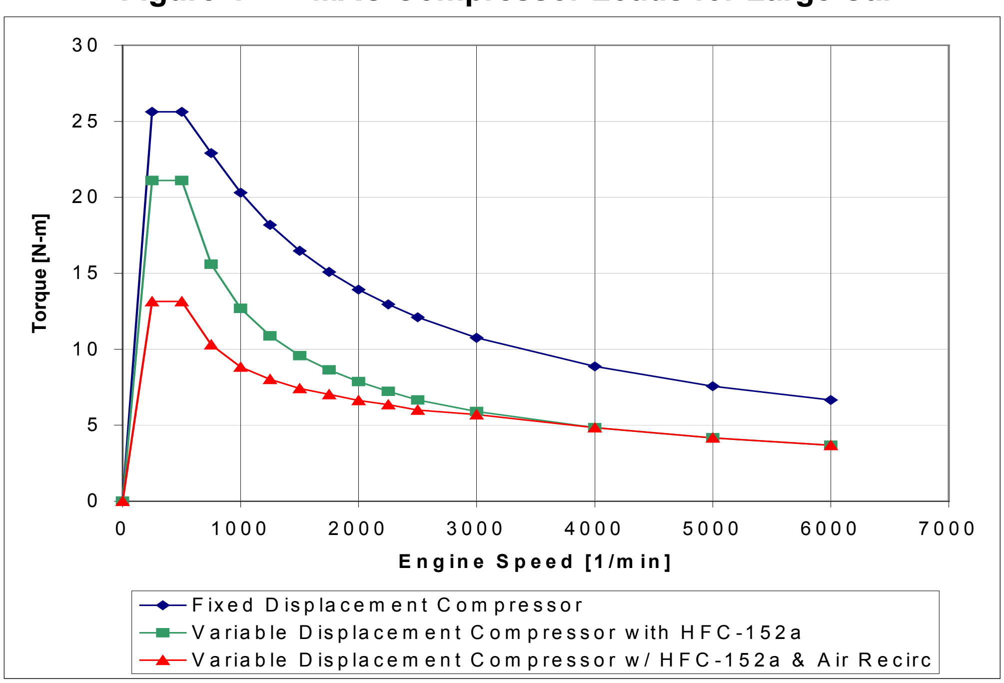
The next step for the improved MAC system was to incorporate the substitute refrigerant, HFC-152a, which transfers heat more efficiently than HFC-134a. Figure 3 shows the system power requirements for HFC-152a relative to HFC-134a. Despite significant scatter, the figure consistently shows the system power requirements for HFC-152a to be lower than that for HFC-134a. The figure also indicates that the relative benefit of HFC-152a increases as specific enthalpy increases. Linear regression shows the relative improvement to range from five to eight percent. Because the average specific enthalpy for our modeling is approximately 61 kilojoules per kilogram, the corresponding improvement is about five percent, as shown in Figure 3.

Figure 3. HFC-152a System Power Demand Relative to HFC-134a System Power Demand



After applying a five percent benefit for refrigerant substitution, the data were converted into class-specific torque curves using the relationship between torque, power, and engine speed. The assumed VDC compressor displacements were 150 cc for the small car, 170 cc for the large car, and 210 cc for the remaining vehicle classes. A torque curve for the large car (170 cc VDC) is displayed in Figure 4. The resulting data were incorporated in the CRUISE simulation modeling for estimation of CO_2 emissions, as depicted in Figure 4.

Figure 4. MAC Compressor Loads for Large Car



However, results from the CRUISE simulation modeling are based on continuous MAC operation, which does not reflect reality. NREL's thermal comfort analysis, which was discussed earlier, also estimated the average frequency of MAC operation throughout the United States for cooling or demisting. For the U.S., the frequency is approximately 34 percent. For California, the frequency is estimated at 29 percent. These results take into account variation in trip behavior by time of day and year, and vehicle miles traveled for each of the seven major cities in California that were analyzed by NREL. Results from each city were then weighted by population figures. Because CO_2 benefits from an improved MAC only apply when the MAC is in operation (as opposed to refrigerant emissions, which may occur when the MAC is not in operation), CO_2 modeling results were adjusted to 29 percent of their modeled value.

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